Simulation of TOGA-COARE Convective Systems Using Single-Column And Cloud-Resolving Models

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Abstract

A Single Column Model (SCM) has been used to simulate the cloud cluster properties observed during Tropical Oceans Global Atmosphere (TOGA) - Coupled Ocean Atmosphere Response Experiment (COARE) and the results have been compared with the profiles obtained from the Goddard Cumulus Ensemble (GCE) Model. The SCM consists of the basic physics of the Goddard Earth Observing System (GEOS), while the prognostic cloud microphysics parameterization scheme is based upon the ECMWF model.

Observed large-scale advective temperature, water vapor, and surface fluxes have been used as continuous forcings to run the SCM and the GCE model. The distributions of precipitation rates are fairly well simulated, but the high cloud fractions are slightly underestimated by the SCM as compared to the GCE model. The cloud liquid water is underestimated but the ice contents are slightly overestimated by the SCM. Results also indicate that the SCM produces mixed profiles of cooling/warming and drying/moistening in the vertical which are highly sensitive to the prescribed surface fluxes. Errors in the temperature and moisture profiles simulated by the SCM are about ± 3 K and 3 g/kg while those from the GCEM are approximately - 1 to -2 K and 1 g/kg at most levels. These results are in good agreement with other SCMs participating in the GEWEX Cloud System Study (GCSS) model intercomparison project.

Sensitivity studies have been carried out to determine what are the major SCM parameterized physical processes responsible for causing the differences between the GEOS SCM and GCE model. Results clearly indicate that, the interaction between various SCM's physical processes are nonlinear, and a mere substitution of the simulated (latent and radiative) heating and moistening profiles from the GCE model may not be able to reproduce the same GCE produced cloud properties. The SCM results have been used to examine the distribution of large-scale cloud cluster properties and their diurnal variation during the disturbed and suppressed periods of convection.

1. INTRODUCTION

One of the most promising methods to test physical parameterizations used in the General Circulation Models (GCMs) is to use field observations together with SCMs and/or Cloud Resolving Models (CRMs) as described by Randall et al. (1996). The SCMs can be considered as a single grid box of a climate model in which field observations may be used to test the parameterization of a physical process. Since the SCMs do not interact with the neighboring grid columns, the effects of the surrounding grid boxes are specified in terms of the large-scale advective forcings to run the SCMs. The advantage of testing a physical parameterization scheme using SCMs is that, errors from rest of the physical parameterizations of the model do not contaminate the results of the scheme being tested. The CRMs use more sophisticated and physically realistic parameterizations of cloud microphysical processes, and allow their complex interactions with solar and infrared radiative transfer processes. The CRMs do not need a cumulus parameterization scheme and can fairly well resolve the evolution, structure, and life cycles of individual clouds. For this reason, the GEWEX (Global Energy and Water Cycle Experiment) formed the GCSS (GEWEX Cloud System Study), and specifically recommended to use CRMs for improving our understanding of cloud representation in GCMs (GCSS Science Plan, 1994). Progress in studying precipitating convective systems in GCSS is reported in Moncrieff *et al.* (1997).

The purpose of the present study is to verify a prognostic cloud microphysics parameterization for large-scale models in conjunction with the Relaxed Arakawa-Schubert cumulus parameterization of Moorthi and Suarez (1993), radiation and turbulence parameterizations used in the GEOS (Goddard Earth Observation System) model. This will be accomplished by using the TOGA-COARE dataset in the framework of a SCM, and comparing the simulated results with those produced by the Goddard Cumulus Ensemble (GCE) Model of Tao and Simpson (1993). The idea is to diagnose and alleviate problems and uncertainties noted in the distributions of cloud liquid water, ice, and downdraft mass flux profiles by Das et al., (1997; hereafter referred to as D97), who studied a prognostic cloud scheme based on the ECMWF model (Tiedtke, 1993; hereafter referred to as T93) using the GATE (GARP {Global Atmospheric Research Program} Atlantic Tropical Experiment) Phase III dataset. While some of the results obtained from these SCM simulations can be verified with observations such as from GATE or TOGA-COARE datasets, many other cloud properties which are difficult to observe, for example, the liquid and ice water contents, and the updraft and downdraft mass fluxes, must be verified with the results from the CRM. Although the CRM results are not reality, they can be judiciously compared with SCM results in order to diagnose problems with the latter.

2. METHOD

2.1 *Cumulus Ensemble Model*

The GCE model has been described in Tao and Simpson (1993). The most distinguishing characteristics of the GCE model are the explicit representation of warm rain and ice microphysical processes, and their complex interactions with solar and infrared radiative transfer processes. The cloud microphysics includes a parameterized Kesseler type two-category liquid water scheme (cloud water and rain). It also has two parameterizations of a three-category ice phase scheme (cloud ice, snow, and hail/graupel; Lin et al., 1983; Rutledge and Hobbs, 1984). Subgrid-scale (turbulent) processes in the CRM are parameterized using a scheme based on Deardorff (1975), Klemp and Wilhelmson (1978), and Soong and Ogura (1980). The effects of both dry and moist processes on the generation of subgrid scale kinetic energy has been incorporated in the model. The GCE model has been linked with an ocean mixed layer model and the TOGA COARE Surface Fluxes Model (wang et al., 1996) for the purpose of assessing the impact of warm sea surface temperatures upon climate change scenarios (Tao et al., 1998).

The GCE model is being linked with other physical models such as: passive microwave radiative transfer and spaceborne precipitation radar models for the purposes of developing and improving retrieval algorithms of precipitation and latent heat release, land surface/soil models in order to understand the impact of landscape heterogeneities on mesoscale circulations and moist processes, and a photo-chemistry model to assess the impact of vertical transport and mixing of important trace species on O_3 production/reduction processes. The GCE model has been used to study the precipitation systems developed in various large-scale environments and the results have generally agreed well with both remote (such as radar and passive microwave) and insitu observations from aircraft penetrations (Simpson et al, 1988, 1996; Adler et al, 1991; Prasad et al, 1995).

For the present study, a 2D version of the model which incorporates stretched vertical coordinates with 46 levels has been used. The model has finer resolutions (about 80 meters) in the boundary layer and coarser resolutions (about 1060 meters) in the upper levels. The grid spacing in the horizontal plane is 1000 meters with 512 grid points.

2.2 *The Single Column Model*

The SCM consists of the basic physics of the GEOS model consisting of the Relaxed Arakawa-Schubert (RAS) cumulus parameterization of Moorthi and Suarez (1993) and is coupled with a downdraft scheme of Sud and Walker (1993). The cloud microphysics has been parameterized by D97 and is based on T93. The short and longwave radiative processes have been parameterized based on Chou (1990, 1992), and Chou and Suarez (1994). The cloud optical properties have been determined following Del Genio et al. (1996). The planetary boundary layer (PBL) has been parameterized using the turbulence level 2.5 order closure based on Helfand and Labraga (1988), and Helfand and Schubert (1995). Since the purpose of this study is to test the cloud microphysics parameterization in the SCM, we shall only summarize here the basic features of this scheme for continuity. A detailed description of the scheme may be found in T93 and D97.

In this scheme, the time evolution of cloud cover and cloud water content is determined by two additional prognostic equations which include their source and sink terms due to diabatic processes as follows:

$$\frac{\partial q_l}{\partial t} = A(q_l) + S(q_l)_{CV} + S(q_l)_{BL} + C - E - P - \frac{1}{\rho}\frac{\partial}{\partial z}(\overline{\rho\omega' q_l'})_{entr} \quad (1)$$

$$\frac{\partial m_f}{\partial t} = A(m_f) + S(m_f)_{CV} + S(m_f)_{BL} + S(m_f)_C - D(m_f) \quad (2)$$

Where, q_l is the liquid water / ice content and m_f is the cloud mass fraction. The terms denoted by A( ) represent advective transport, while the terms denoted by $S(\;)_{CV}$, $S(\;)_{BL}$ represent the sources due to convection and boundary layer processes respectively. C is the rate of condensation / sublimation and E is the evaporation of cloud water/ice. P is the rate of conversion of cloud water into precipitation. The last term in (1) is the flux divergence term due to entrainment processes at the top of the clouds. The fourth term on the right hand side of equation (2) represents the source of cloud formation due to stratiform condensation and the last term denotes dissipation of clouds due to evaporation and turbulent mixing. Clouds are thus allowed to form due to boundary layer processes, detrainment of liquid and ice water from the top of cumulus clouds, large scale ascent, and diabatic cooling. They dissipate through turbulent mixing of cloud with environment, adiabatic and diabatic heating, and depletion of cloud water by precipitation.

The advection terms in the equations (1) and (2) are neglected at present. The source terms of the cloud water species, and mass fraction for cumulus convection and boundary layer processes, are obtained respectively from the model's cumulus and boundary layer parameterization schemes as in T93. After having obtained the source and sink terms, equations (1) and (2) are integrated analytically (see T93) in order to maintain continuity of cloud processes which evolve on short time scales, and to avoid truncation errors.

3. THE TOGA-COARE DATA SET

The TOGA-COARE IOP has provided idealized datasets over the Intensive Flux Array (IFA) which can be used to develop and test cumulus and cloud microphysics parameterizations. Several episodes of intense convection occurred over the IFA during the IOP, which were followed by westerly wind bursts. The clouds and precipitation were modulated by Intraseasonal Oscillations (ISOs) over the warm pool. The most intense convection over the IFA occurred in middle and late December, prior to the peak westerly bursts (Lin and Johnson, 1996b). These convective events were produced mainly from low-level large-scale convergence of the easterlies and westerlies. The observed heat and moisture budgets, and the kinematics and thermodynamic characteristics of the flow during TOGA-COARE have been studied by several authors, i.e., Lin and Johnson (1996a, 1996b), Frank et al. (1996), Chen et al. (1996), Chen and Houze (1997), and Sui et al. (1997a, 1997b) among others. The TOGA-COARE dataset produced by the ECMWF analyses indicated that the model was not able to capture the enhanced sensible heat fluxes, perhaps suggesting the need for an appropriate parameterization of downdrafts (Lin and Johnson, 1996b). Thus, such studies are useful in diagnosing the problems of the physical parameterization schemes of a model.

The period of this study covers eight days beginning at 00 UTC 19 December and ending at 18 UTC of 26 December, 1992, and is based on the large-scale conditions observed over the IFA. This period has also been used by the GCSS working group 4 (WG4) model intercomparison project for CRMs and SCMs (Moncrieff et al., 1997). Both SCM and GCE model simulations were started with the initial condition at 00 UTC 19 December, 1992 . The models were integrated for eight days ending on 18 UTC of 26 December. The GCE model was integrated with a time step of 6 seconds. The SCM was integrated with a time step of 10 minutes for the moist processes (convection and cloud parameterization). The PBL was called at intervals of 30 minutes, while the short and longwave radiation schemes were called at every hour. These time steps correspond to those typically used in the GEOS - GCM. Both models have been integrated starting with the initial observed vertical profiles, and updated by the observed large-scale advective forcings. This allows for a one-way interaction between the large-scale dynamics and model physics. The sensible and latent heat fluxes at the surface were prescribed from the GCE model in order to have the same forcings in the two models.

4. OBSERVED AND SIMULATED FIELDS

The GCE model results indicate that the latent heat fluxes are generally in good agreement with the observed values, while the simulated sensible heat flux is usually overestimated. The tendency of overestimation is usually seen during the active episodes of convection. It should be noted that the observed fluxes were basically measured over a point while the GCE model fluxes are representative of the entire IFA. In order to begin the integration, the observed temperature and moisture profiles at 00 UTC 19 December were used only at the first time step, while the large-scale advective forcings (obtained from observations) were prescribed at all time steps by linearly interpolating from the observed large-scale forcings every six hours. Results indicate that the SCM simulated temperature, moisture, and precipitation rates depend largely upon the prescribed surface fluxes of sensible and latent heat. In order to investigate the sensitivity of the surface fluxes on the simulated errors, several experiments were conducted. Table 1 summarizes four of those experiments.

Experiments	SENS Factor	EVAP Factor
TC1	Observed	Observed
TC2	1.0 * GCE	1.0 * GCE
TC3	1.5 * GCE	1.5 * GCE
TC4	0.5 * GCE	1.5 * GCE

In the first experiment TC1, the observed sensible and latent heat fluxes have been used to run the SCM. The second experiment TC2, has been carried out by using the same surface fluxes as produced by the GCE model. The aim of this experiment is to study how the cloud fields evolve in the SCM when the surface fluxes are same as that in the GCE model. The subsequent experiments TC3 and TC4 have been conducted to minimize the errors in the temperature, moisture, and the rainfall values by varying the magnitude of the surface fluxes prescribed from the GCE model. All these experiments have been conducted by switching on the radiation, convection with cloud microphysics, and the dry convective adjustment instead of the turbulence in the SCM.

Results indicate that the SCM produces large amounts of cooling and drying when the fluxes were used either from observations or as prescribed by the CRM. Experiment TC3 produced a better moisture profile between 600 to 900 mb and temperature profile between 500 and 600 mb. The best results were obtained by TC4 considering all the levels except between 23-24 December when more warming was produced by this experiment. The precipitation rates are relatively better in TC4 as compared to observations. The experiment TC3 produced either zero or very little rainfall compared to observations on 20 December and between 23 to 24 December. The remaining errors are comparable to those obtained by Krueger (1996) from an intercomparison of CRMs and SCMs. In the following subsections, we present the results of simulations using the surface fluxes from TC4.

5. RESULTS

5.1 *Temperature and Water Vapor Profiles*

The SCM generally produces cooling at levels above 850 mb on most of the days, except between 23 and 24 December when the atmospheric column was stabilized and the convection was suppressed. This cooling is comparable to the values produced by most of the CRMs (Krueger, 1996), a MM5 mesoscale model simulation by Su et al. (1997), and the GCE model. Although the cold bias is seen in every model, the magnitude of the drift varies from model to model. The reason for this cold bias is not well understood, but it may be partially due to errors in the observed forcing profiles and surface fluxes (Krueger et al., 1998). The SCM also produces drying at most levels on almost all the days with maximum drying occurring during the stable periods below 700 mb. This is in contrast to the values simulated by the GCE model and other CRMs, which shows slight drying below 850 mb and above 500 mb, but moistening between the two levels. The excess warming and drying produced by the SCM in the lower levels could be attributed to insufficient shallow convective clouds which would remove heat and moisture away from the boundary layer. However, given the sensitivity of the simulated thermodynamic values on the surface fluxes shown earlier, it is hard to attribute this to the deficiencies on the SCM at present. Moreover, the simulations of GATE convective systems by D97 did not show any such errors at the surface. Therefore, the warming and drying in the lower atmosphere may be related to errors in the prescribed large-scale forcings at those levels and the surface fluxes. It may also be noted that the sea surface temperatures were warmer over the TOGA-COARE region than compared to the GATE.

5.2 *Cloud Liquid Water and Ice Contents*

The SCM and GCE model results clearly indicate the existence of four episodes of maximum cloud liquid water and ice contents associated with convective activities. Cloud liquid water is generally confined below 400 mb in the SCM while ice dominates in the upper levels. Comparison between the SCM and GCE model indicates that the former underestimates mean maximum cloud water by about a factor of four. The maximum ice contents, however, are slightly overestimated by the SCM, and are located higher aloft as compared to the GCE model. In the SCM, the liquid water phase is assumed for temperatures above 273 K, while the ice phase is assumed for temperatures below 250 K. For temperatures between 273 K and 250 K, a transition phase containing a mixture of liquid and ice saturation is assumed. The melting of ice across the surface ($T_o = 273K$) is parameterized using a simple relaxation towards the temperature T_0. The differences of the simulated liquid water and ice contents between the SCM and CRM may also be due to the fact that the SCM is one dimensional whereas the GCE model simulations were carried out in two dimensions.

5.3 *Cloud Fraction*

Both the SCM and GCE model produced large cloudiness in the upper levels between 100 and 300 mb, but maximum cloudiness values in the GCE model are simulated about 50 mb above those in the SCM. The distribution of cloudiness by the SCM shows deeper clouds extending from 800 mb to 150 mb, corresponding to strong upward motion. The GCE model shows most of the clouds in the upper levels above 350 mb, and some middle level clouds between 800 to 450 mb. The differential distribution of cloudiness in the vertical between the SCM and the GCE model may be due to differences in the formulations used to compute the cloud amounts by the two models. The SCM computes the cloud fraction based on the prognostic equation (2), whereas in the GCE model, the cloud fraction is determined as follows. At each grid point the cloud mass fraction (m_f) is given by,

$$m_f = 1 \quad \text{if} \quad q_l + q_i > 0.01 q^*\left(\bar{T}, \bar{p}\right); \quad \text{otherwise, } m_f = 0. \quad (3)$$

where q_l and q_i are cloud water and ice mixing ratios and q^* is the saturation mixing ratio over water. The SCM produced a completely clear sky between 23-24 December when the convection was suppressed, while the GCE model produced and/or left some high level clouds from the earlier period. Overall, the maximum amount of clouds produced by the GCE model is slightly higher on average than the amount produced by the SCM.

6. SENSITIVITY OF PHYSICAL PARAMETERIZATIONS

In order to isolate the exact cause for the differences in the simulations between the SCM and the GCE model, and to identify the reasons for producing relatively large errors by the SCM, several experiments were carried out with the physical processes of the SCM. Table 2 presents a summary of the experiments conducted for this purpose.

	RAS	Moist Process	Turbu-lence	Dry Convection	Radiation
TC5	Yes	Yes	Yes	No	Yes
TC6	Yes	Yes	No	Yes	GCE
TC7	GCE	Yes	No	Yes	Yes
TC8	Yes	GCE	No	Yes	Yes
TC9	GCE	GCE	No	Yes	Yes
TC10	GCE	GCE	No	Yes	GCE

In experiment TC5, the turbulence parameterization was switched on and the effects of dry convective adjustment was assumed to be taken care of by the turbulent processes. The next experiment, TC6, was carried out by turning off the radiation parameterization and instead of that, the radiative heating rates obtained from the GCE model were directly substituted into the SCM at every hour interval. Similarly, in TC7, the cumulus parameterization was turned off and the convective heating and moistening rates are prescribed from the GCE model. In TC8, the cloud microphysics parameterization was turned off in the SCM, and instead of that, the stratiform heating and moistening rates were prescribed from the GCE model. The last two experiments TC9 and TC10 were conducted to see how far we could match the observed temperature and moisture profiles in the SCM by using 'brute forces'. At the lower boundary, only 10 percent of the surface fluxes prescribed by the GCE model were used to avoid excess warming and moistening in the SCM. The heating and moistening rates due to both convective and stratiform clouds were prescribed from the GCE model in TC9, while in TC10, the effects of the three major physical processes, i.e., radiation, convection and stratiform clouds wereprescribed from the GCE model into the SCM.

Results indicated that a simple dry convective adjustment in the SCM produces relatively better profiles of temperature and moisture when compared to using a complex PBL parameterization. In other experiments (TC7-TC10), the SCM was run by using prescribed radiative, convective, and stratiform heating profiles which were each individually and obtained from the GCE model However, the results did not improve the simulated temperature and moisture values from the SCM. These results indicate that the interaction between various physical processes are not linear. The convective heating/moistening are the dominant processes. However, their nonlinear interaction with radiation, stratiform, and other physical processes results in different profiles than from observations This indicates that a mere substitution of the heating and moistening profiles from the GCE model may not be able to reproduce the observed temperature and moisture profiles. On the other hand, a systematic improvement of the cloud processes in which the output of one scheme interacts with other parameterizations may be desired. Thus the output of experiment TC4 produced smaller errors as compared to the other experiments.

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